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Research article

Drivers of changing urban flood risk: A framework for action

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ABSTRACT

This study focuses on drivers for changing urban flood risk. We suggest a framework for guiding climate change adaptation action concerning flood risk and manageability in cities. The identified key drivers of changing flood hazard and vulnerability are used to provide an overview of each driver's impact on flood risk and manageability at the city level. We find that identified drivers for urban flood risk can be grouped in three different priority areas with different time horizon. The first group has high impact but is manageable at city level. Typical drivers in this group are related to the physical environment such as decreasing permeability and unresponsive engineering. The second group of drivers is represented by public awareness and individual willingness to participate and urbanization and urban sprawl. These drivers may be important and are manageable for the cities and they involve both short-term and long-term measures. The third group of drivers is related to policy and long-term changes. This group is represented by economic growth and increasing values at risk, climate change, and increasing complexity of society. They have all high impact but low manageability. Managing these drivers needs to be done in a longer time perspective, e.g., by developing long-term policies and exchange of ideas.

1. Introduction

Urban areas face global challenges of flood risk not only due to climate change but also due to the continued densification of residential areas, infrastructure development, and urban sprawl. The urban world population is expected to grow from 3.6 billion in 2011 to 6.7 billion in 2050 (UN, 2018), which means that vast amounts of value in terms of capital as well as a large number of properties are concentrated in increasingly densely built-up urban regions. The global direct economic loss between 1980 and 2013 due to flooding was estimated in excess of $1 trillion (Winsemius et al., 2016). Without action, global damage from floods may increase by up to a factor of 20 by the end of the century (Winsemius et al., 2016). It has been estimated that more than 70% of this escalation can be attributed to economic growth in flood prone areas.

Traditional building techniques and increasing urbanization lead to a greater share of impervious areas that result in increased flood risk, pollution transport, and overloaded storm water pipe systems. However, cities are increasingly built with the intention to use sustainable approaches (Dawson et al., 2011). For this reason, blue-green storm water and nature-based solutions have come to be seen as efficient measures against increasing flood risk in urban areas (Hammond et al., 2015; Haaland and van den Bosch, 2015; IUCN, 2009). However, in the majority of countries, the existing urban environment constitutes

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the absolute major part of invested capital, also for the coming centuries (Bonakdar et al., 2014). Thus, introducing new water structures may in fact increase or at least influence flood risk. In addition, since it is much more complicated to make any changes to existing buildings and infrastructure, the main challenges for increasing the sustainability of urban flood management are related to the existing built environment.

Flood risk may be defined as the product between the probability of flood hazard and the consequence of occurrence of flood event (e.g., Idris and Dharmasiri, 2015; UNDP, 2004) according to

$$\textit{Flood risk} = \text{Pro}\textit{bability of flood hazard} \times \textit{Consequence of occurrence of flood event}$$

where *Consequence of occurrence of flood event* is a function of *Hazard* . *Vulnerability*, the latter here including both exposure and susceptibility of harm (Wisner et al., 2004). Present-day understanding of flood risk focuses on two main drivers, namely climate change and socio-economic growth (Jongman et al., 2012; Ceola et al., 2014). Several studies (Elmer et al., 2012; Winsemius et al., 2016) indicate that socioeconomic growth is by far the dominant driver for flood risk increase. Most studies have focused on rural areas; however, due to the accumulated value and increasing population in urban areas, more research is currently focusing on cities or on both rural areas and cities (e.g., Bruwier et al., 2018; Mustafa et al., 2018a, 2018c). Due to a high degree of impermeable areas, urban areas may be seen as more sensitive to changes in precipitation patterns from climate change (Scholz, 2013). Nonetheless, few studies have focused on a comparison between drivers of changing flood risk in urban areas. A main problem in this context is the interrelationships between urban flood hazard and vulnerability to the impact of floods. For example, urban growth and values at increasing risk may lead to increasing vulnerability for the urban population. This is interrelated to increasing greenhouse emissions from growing urban areas, in turn leading to more climate change and increasing flood hazard from more intense rainfall. In many cases, it is not possible or even warranted to separate between cause and effect of interrelated hazard and vulnerability. Thus, one of the objectives of this paper is to present and discuss a possible methodology to quantify and compare different types of slowly changing urban flood risk components and possibilities for the urban management system to deal with these. The results may be seen as a framework for guiding climate change adaptation action concerning flood risk and manageability.

The proposed framework is a synthesis from a multidisciplinary collaborative research project on Sustainable Urban Flooding (SUrF) led by Lund University, Sweden. The aim is to identify key drivers of increasing flood hazard and vulnerability impacting floods, and provide an overview of each driver's impact on flood risk in relation to its manageability on the city level. In this context, the paper deals with urban flooding caused by local high intensity precipitation (pluvial flood), high flows in adjacent river systems (fluvial flood), and high sea levels (coastal flood). In some instances, one or more of these flood types, can combine to exacerbate a single event.

2. Theory

"A phenomenon that may change the time-averaged state of the flooding system is referred to as a driver" (Hall et al., 2003). Drivers for changing urban flood risk can be under more or less control of stakeholders and managers (Reckien et al., 2015). Fig. 1 illustrates this by grouping examples of various key drivers for urban flood risk according to the degree of control by city stakeholders and managers (Hall et al., 2003). As indicated above, drivers for changing urban flood risk may relate to many factors such as land use, building practices, and climate change. As well, hazards and consequences of floods are often closely interrelated.

As understood from Fig. 1, it is obvious that many drivers are mutually dependent. The built urban environment consists of a mix of public and private buildings and infrastructure that the city partly can control by planning instruments and building practices. Urban sprawl and decreasing permeability are drivers that through different measures also can be partly managed by city authorities. At an intermediate control level, drivers for changing urban flood risk may be affected by national policies and regulations (e.g., Kallis and Butler, 2001). In more abstract terms, drivers may be affected by public perception and regulations within the insurance industry. Global socio-economic development, climate change, and societal complexity are drivers that generally are outside of cities' control sphere but that still are interrelated with urbanization. Climate change is complex as it is affected by global socio-economic and technological development. At the same time, climate change drives urban adaptation addressing changes in pluvial and fluvial conditions. Drivers for changing urban flood risk may be seen as part of an ongoing process where the urban environment and conditions are different by the end of the process as compared to the beginning. In this study, we emphasize slow processes in the time scale of 30–100 years. The change can take place because of drivers within the urban area or be induced by drivers affecting the urban area from the outside.

3. Materials and methods

Seven central but multifaceted drivers for changing urban flood risk were identified through a process of individual brainstorming, literature search, and thereafter a common sort and selection process (Table 1). The drivers were further investigated through multidisciplinary seminar series with additional literature studies between each session. The identified drivers are not independent but can be seen as ongoing processes that partly interact with other drivers. Three of the drivers were identified as affecting urban flood hazard and three drivers affecting the urban vulnerability. One driver was identified as affecting both the flood hazard and vulnerability. Through the above process, the potential impact of each driver was given a rank from insignificant to very high impact for urban flood hazard and vulnerability, respectively. Similarly, the potential manageability for cities was ranked from insignificant to very high manageability.

Manageability is defined as the city's ability to influence the driver in a manner that reduces its strength or makes it less harmful with regard to flood hazard or vulnerability. The city's economical, organizational, and technical pre-requisites as well as its legal power are important aspects of the manageability.

The key driver "Increasingly unresponsive engineering" in Table 1 may need some clarifying explanation. In this notion we include a "traditional engineering approach to flooding is designing single-purpose drainage systems, dams, and levees" (Sörensen et al., 2016). This approach will in the long-term likely increase flood risk and harm the riverine ecosystems in urban as well as rural areas. For this reason, it was included in Table 1 as a key driver for urban flood risk.

Hazard can be defined as "a threatening event, or the probability of occurrence of a potentially damaging phenomenon within a given time period and area" (Barroca et al., 2006). Thus, urban flood hazard is in general a rather straightforward calculation exercise given the urban drainage design and rainfall intensities for a given return period (e.g., Zhou, 2014). On the other hand, quantitative assessment of vulnerability is an ill-structured problem (e.g., Müller et al., 2011; Taubenböck et al., 2008). In the present paper, the authors used a mixed expert and stakeholder participatory approach to arrive at the vulnerability ranks (e.g., Müller et al., 2011). In general, vulnerability may be defined as a combination of exposure, resistance, and resilience (Pelling, 1997; Müller et al., 2011; Meerow et al., 2016). However, studies have shown that exposure often outweighs the other two components. For this reason, and in accordance with the stakeholder interviews, the authors emphasize the exposure side of vulnerability. Thus, the vulnerability levels are estimations of the city's weakness in terms of a given risk magnitude, between insignificant and very high.

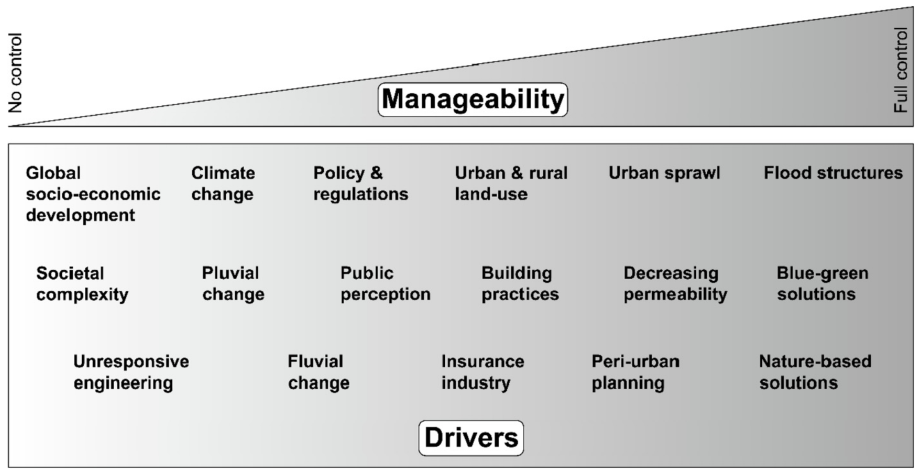

Fig. 1. Examples from literature of drivers for changing urban flood risk with respect to control (partly after Hall et al., 2003).

The identified major drivers for urban flood hazard according to Table 1, constitute different clusters of driver processes representing ongoing processes that have important and long-term effects on urban flood hazard. In a similar vein, the identified major drivers for urban vulnerability, constitute multi-faceted partly interacting processes over different economic, technological, environmental, and socioeconomic scales. In Chapter 4 below, the authors discuss the severity of identified drivers for increasing urban flood hazard and vulnerability. In Chapter 5, each driver's impact on flood hazard and vulnerability and the corresponding manageability on city level are discussed. Chapter 6 concludes the results with recommendations for city management of driver groups.

4. Results

4.1. Drivers of increasing urban flood hazard

In the below, the authors discuss identified major drivers of increasing urban flood hazard (Table 1). Each section defines and discusses the driver with relevant references and estimated potential strength of flood hazard and estimated potential manageability at the city level.

4.1.1. Climate change

Precipitation is a primary factor for pluvial and fluvial flooding in urban areas. Climate variability in general and anthropogenic climate change in particular are important drivers. Thus, potential strength of impact on urban flood hazard is significant. Emission of greenhouse gases (GHG) is the main cause of anthropogenic climate change (IPCC, 2014). Consumption of energy and activities of GHG production are not evenly distributed over the earth and cities are often blamed for contributing to climate change (Dodman, 2009). However, the emissions from cities show a lower GHG contribution per capita than suburban and rural areas (Dodman, 2009; Norman et al., 2006). For example, according to the Swedish census, 31% of the total Swedish population live in towns with more than 100,000 inhabitants (SCB, 2016). Based on the study by Norman et al. (2006), it is not likely that 31% of the Swedish population would lower their GHG contribution due to benefits of living in urban areas. Variability as well as total volumes of rainfall are projected to change due to expected climate change (IPCC, 2014). These factors are very difficult to influence at local or regional scale where the consequences typically occur (e.g., urban flooding). Given the fast and global distribution of GHG, the local production of GHG from a city in relation to the impact received makes this a driver that cities have no direct control over and the potential manageability is low. Consequently, in urban planning, other measures have to be taken to decrease the effects of climatic change.

The mean sea level (together with high water level due to wind, tide, and storm surge) has a direct influence on coastal flooding. The global mean sea level rose by 0.19 m (1.7 mm/year) between 1901 and 2010 (IPCC, 2014). From 1993 to 2010, the rate was 3.2 mm/year. Approximately 75% of this rise can be explained by glacier mass loss and ocean thermal expansion. The sea level will continue to rise in the future, contributing to increased flood risk in low-lying urban areas (Arns et al., 2015). With medium (medium refers to Representative Concentration Pathway RCP4.5) carbon dioxide (CO_2) emissions, there is a moderate risk that adaptation will be needed at many locations to reduce risk for coastal, human, and natural systems. With high (high refers to RCP8.5) CO_2 emissions, there is an elevated risk that coastal protection and ecosystem adaptation reach their limits (IPCC, 2014).

Climate change effects on urban flood risk are different for the different types of flooding covered in this paper:

1) Coastal flooding is caused by high water levels, which in turn are the combined effect of mean sea level and temporary high water levels caused by wind and (often) tide. Wind (speed, direction, and

Table 1
Identified key drivers of changing urban flood risk.

Key driver	Driver type	Scale of influence
Climatic change	Hazard	Regional to global change of precipitation and runoff patterns
Decreasing permeability	Hazard	Urbanization process and urban scale development
Increasingly unresponsive engineering	Hazard	Historical development of today's design criteria of urban drainage systems
Urbanization and urban sprawl	Vulnerability	Expansion of cities into undeveloped areas
Economic growth and values at increasing risk	Vulnerability	Accumulated capital and property value of urban areas
Public awareness and individual willingness to participate	Hazard/Vulnerability	Public and individual participation in urban flood risk reducing measures
Increasing complexity of society	Vulnerability	Continuous and gradual increase in number and intensity of dependencies between infrastructures, systems, and actors

pattern) has not been clearly linked to climate change (IPCC, 2014). Climate change effects on wind are location-dependent and, therefore, even a global mean increase in wind speed may be associated with less wind effects in some regions.

2) Fluvial flooding is caused by extreme surface discharge resulting in high water levels. The main factor, which affects increasing extreme flows, is elevated precipitation. There are strong indications of across-the-globe increasing trends for both maximum streamflow and precipitation (Madsen et al., 2014; Berghuijs et al., 2017; Spierre and Wake, 2010). Similarly, global climate change is expected to increase strength and frequency of extreme precipitation events (Madsen et al., 2014; Westra et al., 2014). However, it should be noted that there is regional variation to these general trends and projections, even to the extent that opposite (decreased flood risk) effects may occur. For northern locations, snowmelt is also important. For both coastal and fluvial flooding, the estimated strength for urban flood hazard is high and manageability at city level is insignificant to low. Besides precipitation, there are other factors affecting streamflow magnitudes such as direct anthropogenic intervention including urbanization. Finally, it should be stressed that the size of the catchment defines the time and space scales involved. High streamflow in small catchments is governed by local and short duration rains, while the opposite is true for large catchments.
3) Pluvial flooding is caused by locally generated surface flow due to high intensity rainfall in urban areas (Scholz, 2010). The mechanisms behind pluvial flooding are in principle the same as for fluvial flooding. However, due to the smaller time and space scales and the urban environment, pluvial flooding is more directly related to rain characteristics. Pluvial flooding occurs when high-intensive cloudbursts saturate the drainage area leading to an excess of water that cannot be absorbed. Pluvial and fluvial mechanisms often combine to more serious flooding in urban areas. Climate change affects both types of flooding, although rainfall characteristics are affected by the smaller space and time scales involved for pluvial flooding (Westra et al., 2014). Since the structure and design of urban areas affect the local climate (Ren, 2015), there is an element of local manageability for pluvial flooding. The level of local influence is considered as weakly manageable for cities.

To summarize the above, climate change influences represent a strong driver impacting on flood hazard. With few exceptions, the projected future climate change increases this hazard for coastal, fluvial, and pluvial flooding. The degree of manageability at city level remains small for climate change effects on coastal and fluvial flooding. For pluvial flooding, a slightly larger manageability is expected at the city level.

4.1.2. Decreasing permeability

The ongoing urbanization process puts pressure on urban development and, hence, on land use in urban areas. The global trend of migration from rural settlements and villages to city regions means that populated areas are growing in size and population density. Concentrating the urban population in existing urban areas through vertical densification and infill projects within the city boundaries is a strong imperative in sustainable urban development (Scholz, 2010; Berg et al., 2012). Urbanization through a densification strategy is often implemented with the aim of providing improved accessibility within walking distance to everyday amenities such as public transport, commercial premises, services, and a lower cost per area unit (Berg et al., 2012; Haaland and van den Bosch, 2015). Urbanization and densification mean, however, that a growing share of the total land area in city regions is allocated to urban development and covered with impervious material when used for buildings and urban infrastructure such as streets, roads, and parking spaces. Green spaces like parks, gardens, and courtyards as well as natural areas, dirt roads, and open roadside ditches are increasingly used for building purposes (Brunner and Cozens, 2013). Moreover, a wide-spread trend in landscape architecture and urban design favours paved areas and hard surfaces instead of plantings and vegetation in general (Scholz, 2010).

Rain falling on urban land is converted to runoff when the corresponding maximum infiltration capacity has been reached (Bastien et al., 2011). The current urban development process often reduces possibilities for soil infiltration as well as evapotranspiration from foliage and open land, thereby enlarging the risk of flooding in urban areas (Ungaro et al., 2014). Urban areas consist of various types of runoff-generating surfaces, conveyance structures such as pipes, swales, and temporary storage facilities. The increase of paved or impermeable surfaces in the urban landscape severely decreases the surface roughness, and consequently increases the risk of flooding (Scholz, 2013). Hence, decreasing permeability means less potential for delayed runoff and a significantly higher risk for flooding and thus, the potential strength of this driver is high.

Lack of adequate maintenance may decrease the effective permeability of an urban hydrological system. Such problems may relate to pipe systems, e.g., blockages in gully pots (ten Veldhuis et al., 2009). Also, sustainable drainage systems (SuDS) may suffer from inadequate maintenance, e.g., clogging of permeable pavement (Bean et al., 2007; Scholz, 2010, 2013; Mak et al., 2017). Insufficient maintenance may be due to absence of funding, but can also be caused by lack of knowledge and unclear responsibilities. Knowledge and awareness of water-sensitive urban planning are crucial to address the risk of flooding. Planners, local officials, and politicians lacking appropriate hydrological understanding might implement densification strategies causing overall decreased permeability and, thereby, severely increase the risk of flooding in urban areas. Private house owners, primarily of single-family houses, might not be aware of the contribution they make toward increased flood risk at a larger scale by, e.g., paving parts of their front gardens. In any case, the potential manageability at city level, must be estimated as rather high.

The natural pathways for water have historically been reconstructed and changed to modify the landscape into a specific urban planning context without focus on the water that inevitably exists or passes through the urban landscape. This lack of attention to urban water flow poses an increased risk of flooding when open surface water is put into, e.g., straight culverts. Among the key parameters that affect the runoff are hydraulic dynamics and scale, site history, soil conditions, and terrain levelling (Backhaus and Fryd, 2013). Substantial increase in runoff can be a consequence if not considering these factors during city development processes. Water velocity may increase two-fold going from overland flow on an average grassland surface to flow on concrete and up to four-fold on new asphalt. Water with increased velocity and volume in the urban landscape will gain momentum and may overflow many obstacles such as street curbs and shallow gutters. In addition, catchment area and water distribution within the catchment highly influence flood risk (Backhaus and Fryd, 2013). The planning for collection and discharging water away from cities has in urban planning traditionally focused on concentrating water into channels and sewage systems. This has meant that water volumes drastically increase in downstream city areas. When cities expand further and new structures are added, this inevitably leads to flooding problems (Bastien et al., 2011; Scholz, 2013).

The impact on risk of flooding posed by a decrease in permeability is known to be substantial. Skougaard Kaspersen et al. (2017) suggest that soil sealing has a significant impact on flood risk, especially from less severe rainfalls. Muñoz et al. (2017) used hydrologic and hydraulic models to study the impact of urbanization on streamflow in Houston, Texas. They concluded that a population growth of 50% in Houston City leads to increased imperviousness of 20%, which in turn means that about 10% more households are possible subjects to flooding concerning a 100-year event. Increased urbanization, even when realized through densification, means an expansion of paved areas used for transportation infrastructure in terms of roads and parking spaces in

central urban areas. Less attention has been paid to land cover for parking purposes on private properties such as front gardens and driveways. A recent study showed how the trend of paving front gardens in the UK increased the risk of surface water flooding during storm events (Kelly, 2018).

In view of the above, the impact on flood hazard from decreased permeability is significant. The possibility to manage densification and urbanization is limited on a municipal level, but the potential to alter land use planning and management, governmental leadership, knowledge levels and potentially to influence the public must be seen as moderate to high.

4.1.3. Increasingly unresponsive engineering

As mentioned above, increasingly unresponsive engineering is defined as using traditional technical solutions where in fact, a transdisciplinary approach (low-impact), could be more efficient (Sörensen et al., 2016). Unresponsive engineering is partly a result of the historical development of today's design criteria for urban drainage systems. Recent studies acknowledge the need for urban engineers to involve alternative ways to manage floods in urban areas (e.g., Zhou, 2014; Sörensen et al., 2016). Cities have to a great extent inherited the urban drainage systems from the past. Urban drainage networks, in a historical perspective, were primarily constructed to convey urban runoff from cities via networks of canals and ditches (Burian and Edwards, 2002). In contrast, human faeces and urine were collected by each household and handled in their backyard gardens in a decentralized manner. Misuse, mismanagement, and lack of maintenance often resulted in smelly canals that had to be covered or substituted by below-ground alternatives. By introduction of water-closets in the 19th century, it was inevitable to employ below-ground drainage systems. This sparked the need for sewer systems that led to the construction of combined sewer networks as centralized solutions to urban drainage challenges (Burian and Edwards, 2002). The adopted centralized approach is the turning point in the history of urban runoff management in Western Europe after which it is coupled to the domestic wastewater problematics. To the authors' belief, this coupling has promoted the surmise of the hydraulic efficiency of wastewater systems (constructed during the late 19th and early 20th century). Even the more advantageous separate sewer network, is based on a similar approach. Most cities have developed their combined sewer network into a mixed combined/separated network. Thus, usually the older central city areas have a combined network and the newer surrounding areas may have a separated system. However, since in most cases the different systems are linked together, some of today's problems have an obvious historical reason.

Generally, pipe systems integrate runoff from all connected subcatchment into one stream, and often, new developments are connected to existing downstream sewers. Therefore, in pipe systems, continuous aggregation and propagation of inflows can easily exceed the hydraulic capacity of the corresponding pipe network. After the developments in engineering of urban drainage systems in late 19th and early 20th century, all newly built pipe systems, either combined or separate, have been designed based on a probability-risk perspective, which is reflected in the form of intensity-duration-frequency curves (Burian and Edwards, 2002). The intensity and duration of the rainfall event describe the physical characteristics of the rainfall, while the frequency is tightly connected to the acceptance level of risk.

In most cities, storm drainage pipes are designed to allow for a risk of flooding once in 2–100 years depending on size of catchment and monetary values at stake. In Sweden, e.g., sewer networks have typically been designed accepting the risk of flooding once every 10 years (SWWA, 2004). For a combined system, this results in combined sewer overflow and basement flooding with wastewater when a rain event exceeds the design recurrence interval (Sörensen and Mobini, 2017). In case of separated sewer systems, surface flooding is the outcome of an overloaded system, which can have severe consequences, since surface flooding interferes and disturbs the mobility and responsiveness of, e.g., urban emergency services (Haghighatafshar et al., 2018). The potential impact of the driver is therefore in general high.

An interesting approach is the dual drainage concept (Djordjević et al., 1999). This concept involves describing the urban storm water drainage system in terms of two main components: a minor system and a major system (Randall et al., 2017). The minor system corresponds basically to subsurface storm sewer pipes and typically take care of runoff from more frequent events. The major system corresponds to streets, natural, and artificial surfaces and should be designed to take care of flows in excess of what the minor system can handle. The two systems are connected at storm water inlets to the drainage system. Modelling approaches have been developed so as to optimize the drainage system to allow for flow regimes including backwater, surcharging, reverse flow, and surface ponding (Randall et al., 2017).

Infrastructural elements of urban drainage, other than pipe systems, are also designed with respect to risk-probability criteria. For instance, during the first half of the twentieth century, both UK and USA invested heavily in flood protection structures such as massive dams, embankments, and detention facilities, which have proved insufficient in later years (Weng Chan, 1997). Apart from the fact that infrastructure is seriously underfinanced and neglected in the USA, such structural measures for flood control are always limited by the assumed magnitude of the design storm. In case of UK and USA, the design storm is often assumed to have a 50-year recurrence interval. This means that in case of more intensive storms, the established infrastructure will not be sufficient. This is especially crucial since stationarity of climatic events does not hold in the era of climate change (Milly et al., 2008). Therefore, future criteria for the design of infrastructure have to account for flexibility and, more importantly, resilience (Carpenter et al., 2012; Sörensen et al., 2016) instead of focusing on a single uncertain event. In view of the above, increasingly unresponsive engineering has a high impact on flood hazard. However, with the efficient management and innovative combination of solutions, the cities appear capable of reducing the strength of this driver in a 30–100-year perspective. The manageability at city level thus appears to be moderate to high.

4.2. Drivers of increasing consequence of urban flood

In the section below, we discuss identified major drivers of increasing urban consequence of urban flood according to Table 1. Each sub-section defines the driver with relevant references, and estimated potential strength of driver, and manageability at the city level.

4.2.1. Urbanization and urban sprawl

Urbanization often brings negative impacts on water quality and hydrology (Qin et al., 2013; Mottaghi et al., 2016). Urbanization is strongly related to decreasing permeability as described in Chapter 4.1.2. However, since this has already been described, the authors focus in this chapter mainly on other factors affecting vulnerability. Urban sprawl refers to the expansion of cities into undeveloped areas and low-density urban development (Mustafa et al., 2018b). There is no single commonly accepted definition of urban sprawl. However, a common denominator for all descriptions is a suburban phenomenon characterized by low density, scattered, and often unplanned housing, usually with large single-use developments and lack of functional open spaces (Larice and Macdonald, 2007). During such developments, much arable land turns into residential areas for suburban population use. Forests and farms disappear and permeable land shrinks. In many cases, the quality of soil is ignored and urban growth occurs on areas not suitable for urban life such as flood banks and contaminated brownfield sites (Mustafa et al., 2018b). Urban areas are densified through a higher compactness and denser population in certain areas. Densification has been recognized as an important factor that statistically increases social exposure to risk (Cutter et al., 2003). The consequence is, in case of flooding, that a relatively large number of people and their belongings

are likely to be affected. On the other hand, the location of buildings plays a key role in attracting developers and people to certain areas such as riversides and coastal areas. However, not only due to their closeness to water, but also because of the soil condition, these areas are usually more exposed to flooding (Pradhan-Salike and Pokharel, 2017; Miller and Hutchins, 2017). Urban densification is increasing considerably and together with insufficient urban drainage design and ageing of infrastructure, it exposes more people and their property to flood risks (Miller and Hutchins, 2017; Sörensen and Mobini, 2017).

It is not easy to quantify the urbanization impact on flooding, since different urbanization scenarios result in different outcomes (Du et al., 2012; Fletcher et al., 2013). Research in general show that flood risk increases significantly by transition from rural to peri-urban areas and further to urban areas (Miller et al., 2014; Prosdocimi et al., 2015; Miller and Hutchins, 2017; Booth, 1991; Aragón-Durand, 2007). In general, long-term planning and control of urban development can mitigate many of these risks. Thus, it can be concluded that urbanization in general represents a moderate to high impact on vulnerability. The manageability for the city can be regarded as moderate, because of the relationship between urbanization, urbanization policy and flood risk.

4.2.2. *Economic growth and values at increasing risk*

Property assets such as houses are typically the largest component of household wealth (Piketty and Zucman, 2014). In a historical perspective, real house prices stayed constant from the nineteenth to the mid-twentieth century, but rose strongly and with considerable cross-country variation in the second half of the twentieth century for the G7 countries (Knoll et al., 2017). Fig. 2 shows real house prices in these countries (Canada, France, Germany, Italy, Japan, UK, and USA) and Sweden between 1970 and2016.[1] As the figure reveals, there has been a substantial increase in property values in several G7 countries. In the UK (Fig. 2A), the house prices have almost increased five-fold, while they have more than tripled in Canada since 1970. Also for France and Sweden, a strong increase in the property values has been noted, especially during the later time period. However, in Germany (Fig. 2B), the real property values have been fairly stable.

Studies show that individuals are often prepared to pay more for houses situated close to watercourses (Benson et al., 1998; Dumm et al., 2016), where the risk of flooding may be high. Another category of asset with high value that can be damaged by flooding comprises vehicles such as cars. The number of cars on the world's roads surpassed one billion in 2010, and is estimated to reach 2.5 billion by 2050 (OECD, 2011). Furthermore, the value of both production and consumption in urban areas is large. Cities like Paris, London, Tokyo, and Stockholm contribute to about 30% of the corresponding country's gross domestic product (OEDC, 2017b).

Hall et al. (2003) found that an increase in flood risk is attributable to a combination of climate change and increasing socio-economic vulnerability, particularly in terms of household and industrial contents as well as infrastructure vulnerability. The analysis predicted an up to 20-fold increase in economic risk by the 2080s for the scenario with the highest economic growth. Rojas et al. (2013) estimated socio-economic impact by combining flood inundation maps with information on asset exposure and vulnerability. They found that future changes in the socio-economic dimension could be as relevant as climate change in increasing future flood risk. On the other hand, Elmer et al. (2012) focused on changes in building values in Germany, and discovered that with the historical exception of the economic effects in Eastern Germany following the German reunification, value developments only had minor influence on the development of flood risk. In view of this, the

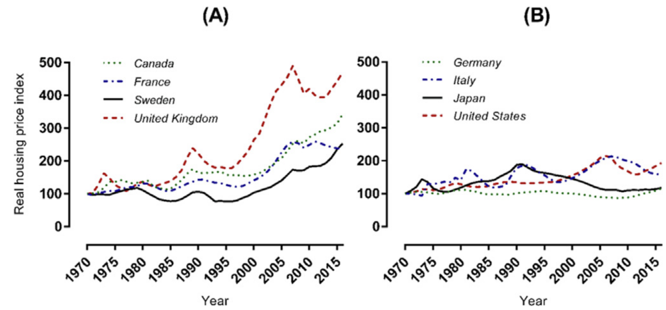

Fig. 2. Real house price indicator for the G7 countries and Sweden, 1970–2016 (1970 = 100; after OECD, 2017).

potential strength of this driver for consequence of urban flood is significant.

An important observation is the balance between new development and climate in mediating future flood risk (Dawson et al., 2011). In many scenario combinations, new development is responsible for over 50% of the increase in risk. This highlights not only the important role of spatial planning and broad-scale development strategies in managing future risk, but also the importance of a much wider range of socio-economic vulnerability. Winsemius et al. (2016) found that over 70% of the increase in world-wide economic losses can be attributed to economic growth in flood-prone areas. Much future risk can be prevented by spatial planning and flood resilient buildings in rapidly growing economies in flood-prone regions. Economic growth, however, not only causes increases in vulnerability s, it also results in better financial ability to prepare for and cope with these events. In view of this and the above, economic growth and increasing exposure of property and other assets are generally seen as moderate to high drivers for increased urban flood consequence. The city, though, has very small but not insignificant manageability on economic growth in a longer time horizon.

4.2.3. *Public awareness and individual willingness to participate*

Commitment and action of diverse stakeholders have been shown to be important for improved storm water infrastructure (e.g., Pradhananga and Davenport, 2017). The range of commitment or action may be everything from giving opinion to taking partial or full responsibility for extreme weather events as a part of societal resilience against flooding. Public participation by community members, e.g. in water resource programs, has several benefits. It typically increases social capital, contributes to trust building for planning processes, builds support for willingness to pay and to follow regulations, and improves implementation (Pradhananga and Davenport, 2017; Larson and Lach, 2008). All types of efficient flood and hazard management require public awareness and a participatory approach (e.g., Correia et al., 1998). This is perhaps especially important in urban areas where the total space is made up of a mix between public and private properties. Research suggests that inclination to mitigate flood loss increases with past damage experience and expectations for the future (Osberghaus, 2014). The distortions in probability estimation for disasters, impact the individual's willingness to participate in mitigation measures and will lead to under-investment in these measures (Volkman-Wise, 2015). But as mentioned above, individuals learn from past events (Viscusi and Zeckhauser, 2006; Shafran, 2011) and update their subjective perceptions of flooding. Public provision of objective probabilities for flooding may thus lead to a more suitable demand and coverage of flood insurances, as well as increasing individual's willingness to participate in mitigation measures. Insurances by themselves can also act as price signals of risk that provides an incentive to individuals to invest in mitigation of flood damage. Botzen et al. (2009) studied the willingness of homeowners in the Netherlands to undertake measures that mitigate flood damage in exchange for benefits on hypothetical flood insurances. The results suggest that many homeowners

[1] The real house price indicator is given by the ratio of nominal price to the consumers' expenditure deflator in each country from the Organization for Economic Co-operation and Development (OECD) national accounts database.

are willing to make investments in mitigation measures. Such examples are, to invest in water barriers, use water resistant building materials, and move central heating installations to floors safe against flooding in favour of a reduction in the insurance premium. Estimates indicate that the prevented damage of these mitigations measures could be substantial, 1 billion euro or larger. Results by Shogren (1990) show that private self-protection is preferred to private self-insurance. Thus, even if a well-functioning flood insurance market does not exist, provision of objective information about flood risks may reduce the damage of flooding for the individual as well as for society. Although, information may improve the likelihood of an individual to make rational decisions, experimental evidence suggests that information can be less efficient than expected. Shafran (2011) found, e.g., that most subjects made choices in response to prior outcomes, despite receiving full information about the risks in advance. Viscusi and Evans (2006) estimated posterior risk beliefs after subjects receive additional information about the risk and found evidence of over-estimation of posterior probabilities.

Globally, there is a large variation in the coverage and possibility to buy flood insurance and thus also in the monetary vulnerability. The majority of losses are not covered by insurance, varying from less than 10% in countries such as Canada and Germany to nearly 100% in France (Lamond and Penning-Rowsell, 2014). In Sweden, regardless if someone is insured or not, a property owner is eligible to claim for the damage after flooding to the corresponding local water utility company according to the Water Law (Naturvårdsverket, 2008). Another reason for not being fully covered by a flood risk insurance may be due to a distorted risk perception as mentioned above. Flood risk is categorized as low probability but high consequence. Results by Johnson et al. (1993) suggest that individuals tend to over-estimate the risk of an event that is more vivid to them, as compared to events that are less intense. Viscusi and Zeckhauser (2006) found that individuals underestimate the risk of natural disasters. Those who have experienced disasters have a higher estimate of the risk, although it is still lower than the true risk value. Findings by Browne and Hoyt (2000) suggest a high correlation between flood insurance purchase and flood losses during the prior year at the state level. The underestimation of the flood risk leads to a too low demand for flood insurance. These results are supported by Browne et al. (2015) who provide evidence that individuals have preferences for insurances covering a high probability but low consequence risk (e.g., bicycle theft) over low probability but high consequence risk. In their study, many more policyholders purchased add-on coverage to their homeowner's insurance to cover the risk of bicycle theft than to cover the risk of losses due to flooding. Households that presume insurance coverage tend not to reduce their mitigation efforts. Similarly, the anticipation of government relief expenditures hinders mitigation merely for some groups of households (Osberghaus, 2014). Public and individual interest to participate in urban flood risk measures can be regarded as moderate to high influence on urban flooding. The public can take direct action in flood mitigation as mentioned above. Concerning a long-term perspective, public awareness also plays an important role through exertion of political pressure through NGOs and from grass root level. Hence, the strength of this driver is estimated as moderate to high. The potential manageability of this driver at city level is estimated to be moderate to high through different kinds of information and awareness campaigns.

4.2.4. *Increasing complexity of society*

Development of society means that planning and management tools for flood mitigation also develops and can become more efficient. However, increasing complexity of society as well means continuous increase in number and intensity of dependencies between infrastructures, systems, and actors (Perrow, 1991; Rasmussen and Svedung, 2000). The steady increase of complexity, sometimes referred to as "creeping dependencies" (Hills, 2005), accumulates and eventually reaches a threshold over which societal actors lose overview, and much of their ability to manage risk and the functioning of society. Literature suggests that three main processes are behind this increasing complexity (e.g., Rasmussen and Svedung, 2000; Carlson and Doyle, 2000; Pírez, 2002; De Bruijne and Van Eeten, 2007). Firstly, is the process toward increasing effectiveness and efficiency (optimization), which has been vital for the development of modern society by increasing cost-effectiveness and liberating resources for other important societal problems. However, optimization entails operating closer to the fringe of conventional practice, approaching the boundaries of safety and sustainability (Rasmussen and Svedung, 2000), and increasing exposure to risk by reducing buffers that could be used to maintain critical functions during disturbances. Hence, optimization means increased efficiency in everyday circumstances, but increased vulnerability to disturbances (Carlson and Doyle, 2000) such as floods. This is particularly pertinent in relation to the increasing use of high-tech solutions in most aspects of human life and society.

Secondly, there is an ongoing process of diversification of actors responsible for maintaining and developing most critical functions in society such as electricity, transportation, and telecommunication. This process is generally called institutional fragmentation (Pírez, 2002; De Bruijne and Van Eeten, 2007) and is closely related to optimization, since involving more actors is expected to increase cost-effectiveness through competition. Finally, the processes of optimization and institutional fragmentation lead to an increasingly aggressive and competitive environment that has the effect of focusing incentives of decision-makers on short-term financial gain rather than on safety and sustainability (Rasmussen and Svedung, 2000), thus undermining incentives for collaboration.

The combination of these processes results in an increasingly complex society that pressures actors to decisions and actions that were previously considered as too risky (Kirwan, 2011). This is not limited to the private sector, but is increasingly influencing the public sector, including urban water management, because of increasing service demands. Brown et al. (2009) show this in their study of past, current, and future urban water management regimes. Moreover, increasing dependencies allow the impacts of unwanted events to cascade throughout society (Little, 2002). For instance, during the 2014 cloudburst in Malmö (Sweden) that brought widespread flooding, a large hospital of national importance was flooded, which nearly resulted in a complete power failure for one of the most critical buildings housing many patients. This, in turn, resulted in a whole range of issues concerning evacuation, as the resources for transportation had also been slimmed down, streets were flooded and traffic was congested. Increasing dependencies do not only transmit consequences of floods and other events, but also the general effects of human decisions and actions (Rinaldi et al., 2001), which complicate flood risk management by making it difficult to foresee the actual effects of policies and practices. There is thus, a clear tendency that this driver has an important influence on urban flooding.

Responsibility can be discussed in a wide range regarding urban flooding. Tennekes et al. (2013) suggested four dimensions of responsibility: ownership, implementation, financing, and liability concerns. Studies have shown that clearer responsibility and a shift of responsibility toward the private sector could increase participation (Klein et al., 2016; Schmitt et al., 2004). Buildings are usually connected to either combined or separated drainage systems. The type of drainage system often causes confusion for private house owners (Klein et al., 2016). In Sweden, the municipalities and the water utility companies try to reduce the land owners' exposure to high water levels from rainfall. However, the rules are different for separated and combined sewer systems. For combined systems, the responsibility for flood protection of the municipality ends at the 10-year design storm. For a heavier rainfall, the landowners have ultimately the responsibility for protecting their own property from being damaged. For property owners with large properties, this may mean that they need to undertake physical measures for dealing with excess water such as building

storm water ponds. However, in the already built environment, this may be difficult. The local authorities may then assist the property owners in their efforts, but should, according to law, never take over the landowners' responsibilities and costs, even if the total costs could be reduced.

Technical development and the internet in conjunction with consumer demands will likely increase society's complexity. Local societies have very limited opportunities to influence the overall trend on the micro and macro levels. Nevertheless, in parallel to this development, work on the national, regional and local level is on-going to protect critical infrastructure in the industrially developed countries, not least through different directives and programs in the USA such as PDD-63 - Critical Infrastructure Protection (Wanis-St. John, 1998). These programs are often broken down in national legislations (EU Commission, 2006, 2009). In Sweden, for example, the local authorities are obliged to identify critical infrastructure dependencies, as a step to secure societies' functionality for different contingencies (MSBFS, 2015).

There is also extensive work taking place to make sure that the societal actors will have a common base for cooperation and command in case of societal contingencies. Measures like these are likely to reduce the negative effects due to complexity and interdependencies between infrastructure systems as well as between actors (e.g., Wolthusen, 2005). Moreover, initiatives are taken to visualize the complexity of the infrastructure and improve the actors' capability to collaborate in different ways, often by making use of geographical information systems (e.g., Wolthusen, 2005; Asproth and Håkansson, 2007; Johnson and Mclean, 2008; Evers et al., 2012; Laugé et al., 2015). These information and support systems are becoming increasingly widespread and are used on the local authority level, hereby increasing, at least in theory, the capability to reduce vulnerability because of higher societal complexity. Still, it is highly uncertain, if these measures to "build barriers" and improve learning are sufficient, or if they can keep pace with the technological developments. To summarize, the complexity of society poses a risk in that consequences affecting one part of a system can spread far and uncontrollably to society at large. The consequences of flood at city level is therefore high. The city has small opportunities to influence the global forces at macro and micro level. Hence, the manageability is insignificant to low.

5. Discussion

The responsibility for managing floods and reducing flood risk have been and remain a challenge for different parts of society. Historically, the responsibility of flood control has developed from groups of individuals to at present, multiple levels of society as complexity of both floods and management has increased. The most central level for flood protection and corresponding management is the municipalities represented by cities (Van Well et al., 2018). The above analysis identified some of the most important drivers for flood risk and in qualitative terms assessed the manageability of these for cities in industrially developed countries. The results, i.e. impact and manageability levels, are presented in Fig. 3 in accordance with driver definitions in Table 1. The figure shows the results in a manageability-impact matrix. The drivers investigated in this paper have an impact that ranges from moderate to very high. The manageability on the other hand ranges from insignificant/low to high. It should be noted that the basically qualitative assessment of impact and manageability is approximate and should not be interpreted in strict terms. The advantage, however, is that drivers of very different origin may be compared and thus, the methodology presented here can be used for decision makers to prioritise planning and management alternatives.

According to Fig. 3, a group of three drivers represent high to very high impact with insignificant to low manageability. These three identified drivers are economic growth and increasing values at risk, climate change, and increasing complexity of society. Obviously, it is very difficult for city authorities to influence these drivers. This result

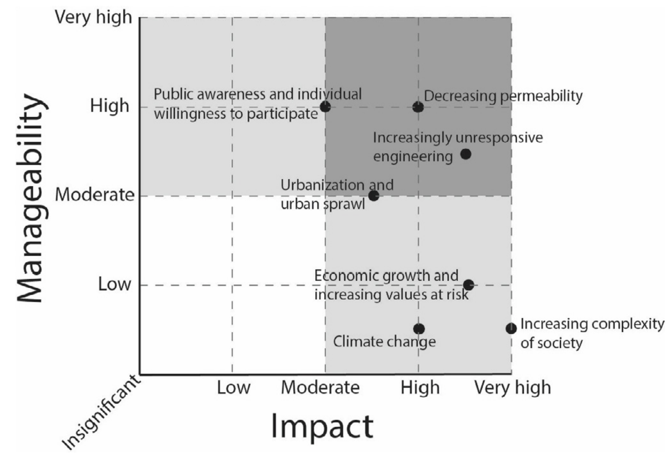

Fig. 3. Identified drivers for urban flood risk with estimated impact and manageability at city level in a time perspective of 30–100 years.

also corresponds with the findings in previous studies such as Elmer et al. (2012), Winsemius et al. (2016), Hall et al. (2003), and Rojas et al. (2013).

Another group of drivers is decreasing permeability and unresponsive engineering. These drivers, on the other hand, represent a high manageability for the cities and with high to very high impact. The final driver group, is the public awareness and individual willingness to participate and urbanization and urban sprawl with moderate impact and manageability for the city.

The three approximate main groups above can be used to define priority of action for flood risk mitigation. The second group above (decreasing permeability and unresponsive engineering) represents drivers that should be of first priority for city authorities to handle. These drivers are manageable at city level and they all have high impact. Thus, managing these drivers should have high priority. The third group is represented by the public awareness and individual willingness to participate and urbanization and urban sprawl. This driver group is manageable for the cities with moderate impact and involves both short-term and long-term measures. Finally, the first of the above groups (economic growth and increasing values at risk, climate change, and increasing complexity of society) has high impact but low manageability. Managing these drivers needs to be done in a longer time perspective, e.g., by developing long-term policies and exchange of ideas, e.g., participating in regional and global forums.

The drivers in Fig. 3 can also be grouped in 1) within-city drivers (decreasing permeability, urbanization and urban sprawl, and unresponsive engineering), 2) household drivers (public awareness and individual willingness to participate), and 3) societal drivers (economic growth and increasing values at risk, climate change, and increasing complexity of society). This division of drivers as well indicates the scale and time horizon for cities to work for mitigation of flood risk.

As exemplified above, the presented methodology can be used to define priorities to mitigate urban flood risk with different time horizons and with different sets of drivers. It is important that drivers like these are discussed and given a relevant priority with a time horizon for action.

Another possibility is to use the present methodology in combination with a mixed expert and stakeholder participatory approach. Maskrey et al. (2016) outlines such an approach to develop flood risk management intervention options. They suggest a participatory modelling technique where the model is co-constructed by flood risk experts and local stakeholders. Suggested participants include residents, local government, regulators, non-governmental organisations, and academics.

6. Conclusions

The results presented herein can be used as a methodology and framework for action regarding mitigation of urban flood risk. Since society's total resources are limited, it is important to develop strategies with different time horizons and priorities for management alternatives to mitigate flood risk. In this respect, the paper presents a methodology to identify and qualitatively compare typical drivers that may be important for flood risk change in cities. Identified drivers for urban flood risk were grouped in three different priority areas with different planning horizons. The three priority areas are as follows:

1) Drivers for urban flood risk of high impact that are manageable at city level. These drivers should receive immediate attention and managed accordingly. Typical drivers in this group are related to the physical environment such as decreasing permeability and unresponsive engineering. These drivers should be given high priority and managed accordingly.
2) Drivers influenced by public awareness and individual willingness to participate and urbanization and urban sprawl are also important but with a somewhat moderate impact on flood risk. These types of drivers are manageable for cities and they involve both short-term and long-term measures.
3) Drivers related to societal complexity, policy, and long-term changes. This group is represented by economic growth and increasing values at risk, increasing complexity of society, and climate change. They have all high to very high impact but insignificant to low manageability. Managing of these drivers needs to be done in a long-term perspective, e.g., by developing long-term policies and participating at regional and global forums.
4) The presented methodology can be used in combination with a mixed expert and stakeholder participatory approach. Suggested participants can include residents, local government, regulators, non-governmental organisations, and academics to develop flood risk management intervention options.

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